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(71) Applicant: E.I. DU PONT DE NEMOURS AND COMPANY [US/US]; 1007 Market Street, Wilmington, DE 19898 (US).

(72) Inventors: BRUNK, Donald, Harvey ; 805 West 32nd Street, Wilmington, DE 19802 (US). HOPPER, Robert, Houston, Jr. ; 504 Palisades Boulevard, Crownsville, MD 21032 (US). LAWSON, James, Robert ; 10 Hickory Lane, Marietta, OH 45750 (US). POPPER, Peter ; 3319 Morningside Road, Wilmington, DE 19810 (US). PRILUTSKI, Gerard, Michael ; Route 1, Box 60, Penn Green Road, Landenberg, PA 19350 (US). WALKER, William, Charles ; 16 West 38th Street, Wilmington, DE 19802 (US). WATT, Teresa, Stoesser ; 112 Warwick Drive, Wilmington, DE 19803 (US).

(74) Agents: HAMBY, William, H. et al.; E.I. du Pont de Nemours and Company, Legal/Patent Records Center, 1007 Market Street, Wilmington, DE 19898 (US).

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(54) Title: CRIMPED FIBER COMPOSITE ARTICLES AND PROCESSES FOR THE PREPARATION THEREOF

(57) Abstract

Shaped articles are disclosed comprising an inner layer of cytocompatible material formed with an aperture therethrough, and further comprising one or more crimped fibers disposed about the exterior surface of the inner layer and within an elastomeric matrix. These articles can be shaped in a variety of configurations and are especially useful as vascular grafts. The articles advantageously exhibit kink resistance and high burst strength. Further disclosed herein are methods for the preparation of the shaped articles.

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TITLE

CRIMPED FIBER COMPOSITE ARTICLES AND PROCESSES FOR THE PREPARATION THEREOF

FIELD OF THE INVENTION

The present invention relates to shaped articles containing crimped fibers within an elastomeric matrix. More particularly, this invention relates to hollow tubes and fibers optionally containing cells on the interior surface, and including crimped fibers within an elastomeric matrix, as well as processes for the preparation thereof.

BACKGROUND OF THE INVENTION

The natural artery is a complex, robust structure which meets demanding physical requirements. It utilizes a composite structure of wavy collagen fiber-like elements together with elastin fibers, lamellae and smooth muscle cells. When the natural artery functions in situ and at low pressure, the wavy collagen elements are not fully extended and the artery is compliant. At high pressure, the collagen elements become extended, and the artery is stiffened thus increasing the burst pressure.

Much attention has been focused on the development of synthetic vascular grafts that approximate the properties of the natural artery. Pradas and Calleja in "An Extensible Modulus-Developing Polymer Composite" (Composites Science and Technology 36, 1989) described a fiber-reinforced polymer composite with a highly non-linear isocronal, stress-strain relation. Its composition was defined as a matrix of poly(ethyl acylate) reinforced with bundles of poly(p-phenylene terephthalamide) fibers of sinusoidal shape. The properties of interest included extensibility, recoverability of any sustained deformation, and a

progressive increment of the isocronal modulus during stretching. However, the experimental fibers of this article are very stiff in comparison to the fibers of the present invention. Further the fiber bundles are merely arranged in a mold with ends fixed after prestretching. The test samples were formed as prismatic bars. There is no description of the shaped articles of the present invention, which include an aperture therethrough and an intricate disposition of the fibers within an elastomeric matrix.

Other efforts to develop synthetic vascular grafts or shaped articles useful within a biological system have resulted in systems having any of a variety of disadvantages. For example, elastomeric tubes which are designed to be compliant without reinforcement may not have adequate burst pressure. Such tubes may further fail catastrophically, with large tears and perforations, and if such devices are implanted within the human body the resultant rapid blood loss could jeopardize the time available for the subject to receive medical attention. Still other grafts and shaped articles are prone to kink upon being subjected to bending forces.

It is an object of the present invention to develop shaped articles such as tubes and hollow fibers that closely approximate the properties of the natural vascular graft. It is a further object of the present invention to provide vascular grafts of composite material that are substantially kink resistant and exhibit high burst pressures (and that do not fail catastrophically). A feature of the present invention is its utility as a wide range of shaped articles. It is an advantage of the present invention to provide a shaped article including a surface that supports cellular attachment and growth. These and other

objects, features and advantages will become more readily apparent upon having reference to the following description of the invention.

SUMMARY OF THE INVENTION

The present invention provides for a shaped article comprising an inner layer of cytocompatible material and having an interior surface and an exterior surface. The interior surface defines an aperture therethrough. One or more fibers are disposed about the exterior surface of the inner layer and within an elastomeric matrix. In an alternative embodiment the invention provides for a shaped article comprising one or more biocompatible crimped fibers disposed about a longitudinal axis and having an interior surface and an exterior surface. The interior surface defines an aperture therethrough and the fibers are disposed within a biocompatible elastomeric matrix.

In both of the aforedescribed embodiments the fibers may be linearly disposed about a longitudinal axis (and for example in a helical pattern or a radial pattern), non-linearly disposed about this axis, or even disposed in a braided pattern thereabout. The shaped article may additionally comprise one or more fibers axially oriented along the longitudinal axis.

Processes for the preparation of shaped articles according to the invention are also disclosed and claimed herein. One such process comprises forming an inner layer of cytocompatible material and having an interior surface and an exterior surface, the interior surface defining an aperture therethrough. One or more fibers are disposed about a fixture configured as the exterior surface of the inner layer to form a reinforcing layer thereon. The reinforcing layer is transferred from the fixture to the exterior surface of the inner layer. The reinforcing layer is next heated

sufficient to crimp the fibers of the reinforcing layer. An elastomeric matrix is then applied to the reinforcing layer.

DETAILED DESCRIPTION OF THE INVENTION

The various components of the shaped articles according to the invention may be prepared from a variety of polymers. The inner layer of cytocompatible material when included as a component of the shaped article is a polyether ester, such as a copolymer of repeating units of poly(tetramethylene ether glycol) and repeating units of poly(butylene terephthalate). In another preferred embodiment the inner layer is a polyether urethane urea, such as a copolymer of repeating units of poly(tetramethylene ether glycol) and repeating units of the reaction product of ethylene diamine with methylene bis(4,4'-diphenylisocyanate).

The fibers used within the present invention are typically polyester. These fibers are disposed within an elastomeric matrix, which preferably comprises a copolymer of repeating units of a soft segment and repeating units of a crystallizable hard segment. The soft segment is preferably poly(tetramethylene ether glycol), and the crystallizable hard segment is preferably either poly(butylene terephthalate) or the reaction product of ethylene diamine with methylene bis(4,4'-diphenylisocyanate).

Moreover, the elastomeric matrix and/or the inner layer may be porous. Porosity desirably provides for the exchange of the nutrients, fluids and other materials between the inside and outside of the shaped article. Of course, some uses of shaped articles according to this invention require that the formed elastomeric matrix not exhibit porosity, and such a feature is additionally contemplated herein.

The shaped article described herein and including the inner layer of cytocompatible material may additionally have cells attached to the interior surface of the inner layer. The cells may be any of a wide variety including fibroblasts, adipose cells, endothelial cells, epithelial cells, organ parenchymal cells, muscle cells, nerve cells and mixtures thereof. Particularly preferred are shaped articles wherein the cells attached thereto are endothelial cells.

The surface characteristics of the inner layer affect the attachment, growth and securedness of the various cells supported by the substrate. For example, if the layer texture is rough (defined generally as having a variety of indentations and other features so that it is not topically uniplanar) the cells are not afforded a suitable base to promote desirable attachment to the surface. In particular, the texture with such features in the range from about 0.1 to 50 μm is detrimental to endothelial cell attachment and growth. However, and preferably if the layer is smooth in texture, the various cells generally attach to the surface; further the cells are capable of growth on a smooth surface and are secured to the surface sufficiently to withstand certain levels of flow rate and pressures of fluids that move relative to the cells in situ. These cells may function to prevent blood clotting.

Another parameter affecting cell attachment and growth is the porosity of the interior surface of the inner layer. At one extreme, the surface may have no porosity; that is, the surface has no apertures of any type therein. A nonporous surface promotes adhesion, growth and attachment of the cells, and it is a requirement for shaped articles that must insulate the flow of fluids (i.e., no exchange of materials across

the polymeric substrate). At the other extreme, a surface with very large pores is not a suitable substrate for the attachment and support of cells. However, there is a range of pore size of the surface that is suitable for cell attachment while simultaneously providing a means for the exchange of fluids through the substrate. Typically the useful range of porosity of this invention is from 0.01 to 10 μm.

A preferred shaped article according to the invention is a vascular graft. Vascular grafts in a broad sense connect a vessel to another portion thereof or to another vessel. Accordingly the grafts are useful in shunt arrangements where blood is routed from a location on a vessel and returned to the same or another portion of the vessel. Additionally the graft may cross over from one vessel to another vessel, acting in a bridge capacity. One contemplated use of the present vascular graft is with bypass procedures wherein the graft connects an artery to another portion thereof or to another artery. A further utility of the present vascular grafts is for the enhancement of peripheral circulation. In such an application the graft connects a blood vessel to another portion thereof or to another blood vessel.

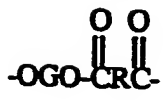
While the various fiber orientations and component polymers disclosed earlier herein are deemed suitable for vascular grafts, certain combinations of these physical features are considered most appropriate for vascular grafts in particular. By "linear" disposition it is meant that the fibers are wound or braided at a constant angle. In contrast, the term "nonlinear" means that the fibers are laid down at a variable angle (that is, two or more angles measured from the longitudinal axis of the inner layer to the axis of the fiber are

evident). The term "radial" encompasses angles normal to the longitudinal axis ± 5 degrees. Most preferably, the fibers are braided. The inner layer of the vascular graft may be formed of materials as indicated earlier. The fibers of the vascular graft are preferably polyester. Moreover, the elastomeric matrix of the vascular graft is preferably a copolymer of repeating units of poly(tetramethylene ether glycol) soft segment and a crystallizable hard segment of either poly(butylene terephthalate) or the reaction product of ethylene diamine with methylene bis(4,4'-diphenylisocyanate). Other soft segments and crystallizable hard segments are considered useful herein. The vascular grafts herein find particular utility in having attached thereto endothelial cells.

It has been determined that vascular grafts according to the invention exhibit physical properties that compare favorably to those of the natural human artery or vein. Accordingly, the presently claimed vascular grafts exhibit a compliance of greater than or equal to 1 percent per psi and a burst pressure of greater than or equal to 15 psi.

The selection of poly(tetramethylene ether glycol) soft segment and poly(butylene terephthalate) hard segment for components of the present invention is one of a family of thermoplastic copolyester elastomers considered useful for the present invention.

According to this invention there is provided a thermoplastic copolyester elastomer consisting essentially of a multiplicity of recurring intralinear long chain and short chain ester units connected head-to-tail through ester linkages, said long chain ester units being represented by the following structure:



(a)

and said short chain ester units being represented by the following structure:

(b)

wherein:

G is a divalent radical remaining after removal of terminal hydroxyl groups from poly(alkylene oxide) glycols having a carbon to oxygen ratio of about 2.5-4.3, a molecular weight above about 400 and a melting point below about 60°C;

R and R^1 are divalent radicals remaining after removal of carboxyl groups from dicarboxylic acids having molecular weights less than about 300; and

D is a divalent radical remaining after removal of hydroxyl groups from a low molecular weight diol having a molecular weight less than about 250;

with the provisos that the short chain ester units constitute about 15-30% by weight of the copolyester, at least about 80% of the R groups must be 1,4-phenylene radicals, at least about 80% of the D groups must be 1,4-butylene radicals, and the sum of the percentages of the R groups which are not 1,4-phenylene radicals and of the D groups which are not 1,4-butylene radicals cannot exceed about 20%.

The term "long chain ester units" as applied to units in a polymer chain refers to the reaction product of a long chain glycol with a dicarboxylic acid. Such "long chain ester units", which are a repeating unit in the copolyesters of this invention, correspond to the Formula (a) above. The long chain glycols are polymeric glycols having terminal (or as nearly terminal as possible) hydroxy groups and a molecular weight above about 400 and preferably from about 400-4000. The long chain glycols used to prepare the copolyesters of this invention are poly(alkylene oxide) glycols having a carbon to oxygen ratio of about 2.5-4.3. Representative long chain glycols are poly(1,2- and 1,3-propylene oxide) glycol, poly(tetramethylene oxide) glycol, random or block copolymers of ethylene oxide and 1,2-propylene oxide (used in proportions such that the carbon to oxygen mole ratio in the glycol exceeds 2.5) and random or block copolymers of tetrahydrofuran with minor amounts of a second monomer such as methyltetrahydrofuran (used in proportions such that the carbon to oxygen mole ratio on the glycol does not exceed about 4.3).

The term "short chain ester units" as applied to units in a polymer chain refers to low molecular weight compounds of polymer chain units having molecular weights less than about 550. They are made by reacting a low molecular weight diol (below about 250) with a dicarboxylic acid to form ester units represented by Formula (b) above.

Useful polymers having a poly(tetraethylene ether glycol) soft segment and a hard segment of poly(butylene terephthalate) are described in U.S. Patent 4,906,729 which is incorporated by reference herein. It is to be understood that in selecting a polymer according to the reference or otherwise according to the invention, the

polymer must be substantially free of contaminants and impurities. For example, the polymers must be substantially free of silicon. This is not to say that additives cannot be incorporated into the polymer; depending on the desired properties, certain additives may be appropriate for addition. Rather, and it is understood by those skilled in the art, these polymers must for some purposes be biocompatible and accordingly types of additives and levels of impurities must be carefully controlled.

It is essential that at least about 80 mole percent of the dicarboxylic acid incorporated into the polymer be terephthalic acid and at least about 80 mole percent of the low molecular weight diol incorporated into the polymer be 1,4-butanediol. Thus, at least 80% of the R groups in Formulae (a) and (b) above are 1,4-phenylene radicals and at least about 80% and the D groups in Formula (b) above are 1,4-butylene radicals. A further requirement in making the polymers of this invention is that the sum of the percentages of the R groups which are not 1,4-phenylene radicals and the D groups which are not 1,4-butylene radicals cannot exceed about 20%. For example, if 20% of the low molecular weight diol molecules used are other than 1,4-butanediol, then all of the dicarboxylic acid used must be terephthalic acid, or if 10% of the low molecular weight diol molecules used are other than 1,4-butanediol, then at least about 90% of the dicarboxylic acid must be terephthalic acid. Copolyesters having fewer 1,4-butylene terephthalate units than is assured by the foregoing proportions do not have sufficiently rapid hardening rates. The D and R units which are not 1,4-butylene and 1,4-phenylene, respectively, can be derived from any of the low molecular weight diols or dicarboxylic acids named above.

The copolyesters of this invention contain about 15-30% by weight of short chain ester units corresponding to Formula (b) above, the remainder being long chain ester units corresponding to Formula (a) above. When the copolyesters contain less than about 48% by weight short chain units, the tear strength and solvent resistance of the copolyesters fall to undesirably low levels and when the copolyesters contain more than about 65% short chain units, the low temperature properties worsen and the copolyesters become less elastomeric. The optimum balance of properties is obtained when the short chain ester content is about 20-25%.

The preferred copolyesters of this invention are those prepared from dimethylterephthalate, 1,4-butanediol and poly(tetramethylene oxide) glycol having a molecular weight from about 600-2000.

The polymers described herein can be made conveniently by a conventional ester interchange reaction.

The selection of poly(tetramethylene ether glycol) soft segment together with the reaction product of ethylene diamine with methylene bis(4,4'-diphenylisocyanate) as the hard segment is one of a family of polymers considered useful for the present invention.

Useful polymers having a poly(tetramethylene ether glycol) soft segment and a hard segment of the reaction product of ethylene diamine with methylene bis(4,4'-diphenylisocyanate), are described in U.S. Patents 4,296,174 and 3,428,711 which are incorporated by reference herein. It is to be understood that in selecting a polymer according to these references or otherwise according to the invention, the polymer must be substantially free of contaminants and impurities. For example, the polymer must be substantially free of

silicon. This is not to say that additives cannot be incorporated into the polymer; depending on the desired properties certain additives may be appropriate for addition. Rather, and it is understood by those skilled in the art, these polymers must for some purposes be biocompatible and accordingly types of additives and levels of impurities must be carefully controlled.

The segmented polyurethanes contain the recurring linkage -O-CO-NH-. A substantial number of the urethane nitrogens may be joined to radicals, usually aromatic, which are further attached to a ureylene residue -NH-CO-NH-. Generally speaking, these segmented polyurethanes are prepared from hydroxyl-terminated prepolymers such as hydroxyl-terminated polyethers of low molecular weight. reaction of the prepolymer with a stoichiometric excess of organic diisocyanate, preferably an aromatic diisocyanate, produces an isocyanate-terminated polymeric intermediate, which may then be chain-extended with a difunctional, active hydrogen-containing compound, such as water, hydrazine, organic diamines, glycols, dihydrazides, amino-alcohols, etc.

The segmented polyurethane elastomers are comprised of "soft" segments, derived from polymers having a melting point below about 50°C, and a molecular weight of above about 600, and "hard" segments, derived from a crystalline polymer having a melting point above about 200°C, in the fiber-forming molecular weight range. Most of such polyurethanes, when in filament form, have a high elongation and tensile recovery and a low stress decay. This invention is particularly effective when applied to the fibers derived from organic diamines and described in U.S. 2,929,804, and this category of fiber is preferred in the practice of this invention.

From a standpoint of commercial availability, the preferred hydroxyl-terminated prepolymers are the polyether glycols, and random or blocked copolymers of tetrahydrofuran with minor amounts of a second monomer such as methyl tetrahydrofuran. For the purposes of this invention, the preferred polyether glycols include polytetramethylene ether glycol and glycols include polytetramethylene ether glycol and glycols of polytetramethylene ether having urethane groups in the polymer chain.

The hydroxy-terminated soft segment is generally reacted with an organic diisocyanate which is preferably an aromatic diisocyanate, as indicated hereinabove. Suitable aromatic diisocyantes include p-phenylene diisocyanate, 4,4'-biphenylene diisocyanate, p,p'-methylenediphenyl diisocyanate, and p,p'-isopropylidenediphenyl diisocyanate. Aliphatic and cycloaliphatic diisocyanates, for example, 4,4'-methylenedicyclohexyl diisocyanate, are also suitable. The diisocyanates may contain other substituents, although those which are free from reactive groups other than the two isocyanate groups, are ordinarily preferred. The organic diisocyanate is not critical for this invention.

The difunctional, active hydrogen-containing compounds suitable as chain-extenders include a wide variety of compounds, as indicated hereinabove. Organic diamines are preferred. Suitable diamines include ethylenediamine, tetramethylenediamine, 1,2-propylenediamine, m-xylylenediamine, p-xylylenediamine, cyclohexylenediamine, piperazine, and many others. Symmetrical aliphatic diamines are preferred, but aromatic diamines, e.g., p-penylenediamine and p,p'-methylenedianiline, may be used.

It should be noted that it is not desirable to incorporate polyester soft segments into the polyurethane based polymer. Additionally, and as pertaining to copolymers wherein the soft segment is poly(tetramethylene ether glycol) and the hard segment is either poly(butylene terephthalate) or the reaction product of ethylene diamine with methylene bis(4,4'-diphenylisocyanate), it is notable that these copolymers may be used as elastomeric matrices.

Braiding is considered herein as a fabric forming technique that allows both controlled orientation of the reinforcing geometry and the desired fabric construction. A braid with the crimped fibers is analogous to that of collagen in the native artery. Braiding gives the preferred orientation. The cross-overs in the fabric provide structural integrity (physical crosslinks) at large strains, analogous to the crosslinks in collagen and between collagen fibrils. The crimp in the fibers provides a low modulus at low strain region analogous to the waviness in the collagen reinforcing elements in the natural artery.

Two techniques have been developed to create the desired crimped fiber braid. Each fabrication technique is described below.

The first approach to developing a crimped fiber braid was to braid uncrimped fibers on a fixture, slide the uncrimped braid onto the inner layer shaped article (such as a vascular graft), and then crimp the fibers using convection, conduction or irradiation (typically hot air or water). Braiding the uncrimped fibers on a fixture was done using conventional braiding techniques. Sliding the uncrimped braid onto the inner layer of the vascular graft without dishevelling the braid is desired. To accomplish this a fixture is used so that the braid could be slid off the fixture directly onto

the inner layer without rearrangement. The fixture comprises one or more pieces designed to collectively resemble the exterior surface of the inner layer. The pieces are then removed sequentially as the reinforcing layer is transferred over the inner layer. The braid has a very strong tendency to stick to the inner layer since the inner layer is typically wet. (The inner layer is desirably kept wet to avoid drying out and changing the desired surface morphology). Because of the problem of a braid tightening up on the fixture upon the application of tension, in one embodiment a hollow fixture was devised which can be fit over the inner layer and that could be split in two pieces lengthwise so that the braid could be released from the fixture by moving one piece relative to the other to remove the tension.

In a preferred design, the fixture comprises one or more rods spaced in a collective configuration as the exterior surface of the inner layer, and appropriately supported. The rods in the fixture allowed the uncrimped braid to be supported by only line sources. The rods of the fixture would be removed individually in a way that minimized braid dishevelment. (For example and in a configuration of eight rods, slowly remove one rod, as the tension on the rest of the braid will minimize dishevelment. Then remove the rod opposite the first rod, followed by a rod at 90 degrees to the first rod, the rod opposite the third rod, any of the remaining rod, the rod opposite the fifth rod, and then the last two rods. By following this pattern of rod removal, dishevelment is minimized. The potential for dishevelment is greatest during the removal of the last rod since the braid has a tendency to drape around it, increasing friction. Rotation of the rod while withdrawing it minimizes dishevelment.)

The fixture of rods allowed the uncrimped braid to be deposited fairly uniformly on the inner layer. The rods may be positioned about the exterior surface of the inner layer, in which case the braid engages the inner layer as the rods are removed. The rods may also be positioned in other areas relative to the inner layer. The uncrimped braid would then be crimped by heating it with a hot air gun. The mandrel supporting the inner layer and the uncrimped braid would be rotated during crimping to ensure uniformity.

Further, the rods may be flexible so that a mandrel may be placed inside the rods in a tight fit (the rods flex to accommodate the mandrel). This ensures a more compact assembly. This is useful in embodiments wherein there is no inner layer; the fibers and elastomeric matrix are compactly fitted over the mandrel to produce a structure closely approximating the size of the mandrel external surface.

It was discovered that the yarn in the braid could still be crimped. The crimpable yarns in knit constructions could not be crimped by the application of heat. There was sufficient mobility and absence of tension in the braid construction that the yarn was still fully crimpable.

This technique has the additional advantage of enabling the finish on the yarn to be easily removed while the crimped fibers are on the fixture. Since only a minimum of yarn handling occurs afterwards, the finish can be removed at this point.

The amount of crimp in the final composite is determined by the dimensions of the fixture and the inner layer.

This braid construction technique is particularly well suited to making "sparce" braids since the braid itself does not have to have sufficient mechanical

integrity to permit handling. Thus it should be moderately easy to make compliant grafts with this reinforcement technology.

The second approach to developing a crimped fiber braid was to use precrimped fiber and braid over a stationary fixture. These braids were made by pulling the braid off the fixture as it was made. In this way a continuous braid of arbitrary length could be made. This approach requires a large number of carriers. Also it is essential to use a high denier yarn for the braid to have sufficient integrity that minor handling will not lead to massive dishevelment. The amount of crimp in the final reinforcement fibers would be determined by the diameter of the rod on which it was made.

This method of braiding a continuous tube of bicomponent fibers is necessary because fibers cannot be braided into the required structure by conventional means (the process tends to straighten their spring-like geometry). Furthermore, it is difficult to produce continuous lengths of tubing because the braided tubes deform under very low forces.

In the present approach the braid is developed at ultra low tension by eliminating the conventional retraction mechanism on the carriers and utilizing the elongation of the yarns to perform the retraction function.

Forming continuous lengths of a very compliant tube is done by braiding on a tapered, stationary mandrel and then sliding the formed tube off the free end.

One illustration of this technique uses a standard circular braider modified to operate under extremely low tensions (approximately 2 gms or 0.1 gm/denier). A specially designed slip mandrel allows the braid to be formed with a uniform microstructure.

The tubes were made of bicomponent fibers in braids with high inclination angles. These braids could deform by two mechanisms - angulation (typical of braids) and crimp pull-out (typical of bicomponent fibers).

The braiding process further included reducing the yarn tension to a very low level and adding a mandrel to "take-off" the very fragile tube as it is being formed.

Very low tensions are needed for this structure to avoid premature crimp pullout. Braiding at standard conditions would produce a very tight, unacceptable structure without the required high extension. Very low tension braiders are commercially available, but they are generally restricted to a low number of carriers and very small structures (e.g., eye sutures).

The present low tension braiding was accomplished by locking the ratchet mechanism on the carriers, which controls the "reservoir" system. This deactivates the carrier retraction function. Braiding can still be done in this case because the yarn elongation and recovery provides the same function.

Conventional take-off elongates and distorts the braid so the machine action had to be modified. A stationary mandrel in which the fabric slips off the end is used.

The mandrel consists in one embodiment of a glass tube with a tapered end which is positioned a precise distance from the point of braid formation. The tube is contour-tapered on the downstream end to permit the braid to slide off. The amount of braided material on the mandrel must be set between tight limits. If this length is too short, the braid collapses on takeoff and if it's too long, it develops too much frictional drag. For the conditions used, the optimum length was found to be approximately 1 inch.

Process Conditions (for the structure described above)

Mandrel material - glass tube
Mandrel geometry - 8 mm OD
End contour - gradual taper to 2 mm Dia over 25 mm length
Braid Contact Length - 20 mm
Machine - 32 carrier circular (Mossberg)
Takeoff Ratio - 40 picks/in
Carriers - No. 2 without retraction system

A range of structures could be braided in this way. For example, we could vary the tube diameter and braid angle.

These braids also need to be placed over the inner surface layer. The braid adheres to the wet inner layer and so a tapered tube is placed over the end of the inner layer which is supported on a mandrel. The braid is urged over the tapered tube until it is properly arranged on the inner layer.

An advantage of this braid fabrication method is the ability to form long continuous braids of excellent uniformity and mechanical integrity.

The presently claimed invention will become more readily understood upon having reference to the examples herein.

EXAMPLES

In the examples, several physical tests were conducted according to known and accepted ASTM procedures. Kink resistance was measured by bending the tube around cylinders of different radii without placing tension on the tube. The "kink radius" is the radius of the smallest cylinder around which the tube could be bent without a sharp change in the curvature of the tube, i.e., a "kink". Compliance is the rate of change of the inner diameter of the tube as a function of

pressure. The compliance of the tube was determined by measuring the outer diameter of the tube as a function of pressure. Constant cross-sectional area was assumed. Burst pressure is measured by filling the tube with water and pressurizing the tube with water until it bursts. The pressure at which the tube bursts is designated the burst pressure. In addition, the failure mode of the samples was judged by visual observation of the physical appearance of the tube or fiber. Where damage of the specimen was greater than 4 mm, failure was labelled "catastrophic". "Moderate" failure is indicated for damage of about 1 mm. "Localized" failure is indicated where failure is adjudged less than 0.5 mm. The results of the tests for the examples are listed in Table I herein.

Note that a polyether urethane urea may be prepared according to the teachings of U.S. Patent No. 4,296,174 (e.g., Example I, first paragraph).

COMPARATIVE EXAMPLE 1

A polyether urethane urea (PEUU) polymer solution containing approximately 30 wt. % PEUU dissolved in dimethyl acetamide (DMAC) and containing 15% suspended salt (NaCl) was used to form a hollow tube by a dry jet wet spinning process as is readily understood and appreciated by those skilled in the art. The polymer solution/suspension was passed through a cylindrical annulus. Water, which is miscible with DMAC and a nonsolvent for the PEUU, was passed through a center orifice. Thus, as the polymer solution passed through the spinneret, the inner surface of the solution contacted a coagulant, water. The exterior surface of the extrudate did not contact a coagulant until the extrudate was 10 millimeters from the surface of the spinneret. The coagulated extrudate was washed in sterile, filtered water, then boiled in water to remove

the salt, then further washed to remove residual solvent and salt. This material is subsequently referred to as the PEUU surface layer.

EXAMPLE 1

A heat-crimpable bicomponent polyester fiber was braided over a fixture. The PEUU surface layer described in Comparative Example 1 was slid over a glass rod which was 4 mm in diameter. The glass rod containing the surface was placed inside the fixture. The rods supporting the braid were then removed to deposit the braid on the surface layer with a minimum of yarn dishevelment. The rod, surface layer and braid were then heated by a hot air gun to cause the development of crimp in the fibers. This resulted in a surface layer covered with a crimped fiber braid. This material was dipped in a 10% PEUU/DMAC solution, drawn through a die and placed in a water bath to coagulate the outer layer. After coagulation, the excess water on the resulting structure was removed and the material dipped in a 5% PEUU/DMAC solution. This material was coagulated and washed over several days to remove trace amounts of the solvent.

COMPARATIVE EXAMPLE 2

A dry blend consisting of 45 weight percent sodium chloride and 55 weight percent of a copolymer of poly(tetramethylene ether glycol) and poly(butylene terephthalate) was prepared by melting the polymer and blending it with the salt. The blend was processed into pellets using a Werner & Pfleiderer 35 mm twin screw extruder according to techniques readily understood and commonly practiced by those skilled in the art. The pellets were processed into tubing. A sample of tubing whose initial outside and inside diameter were 4.57 and 3.56 mm, respectively, was placed in boiling water for a total time of 3 hours to extract the salt. The water

was changed twice during this time period. After salt extraction, the outside and inside diameters were 5.06 and 3.93 mm, respectively, and the density was determined to be 0.479 g/cm^3. This material is referred to as the polyester elastomeric surface layer.

EXAMPLE 2

A heat-crimpable bicomponent polyester fiber was braided over a fixture. The polyester elastomer surface layer described in Comparative Example 2 was slid over a glass rod which was 4 mm in diameter. The glass rod containing the surface was placed inside the fixture. The rods supporting the braid were then removed to deposit the braid on the surface layer with a minimum of yarn dishevelment. The rod, surface layer and braid were then heated by a hot air gun to cause the development of crimp in the fibers. This resulted in a surface layer covered with a crimped fiber braid. This material was dipped in a 10% PEUU/DMAC solution at 90°C, drawn through a die and placed in a water bath to coagulate the outer layer. This material was washed over several days to remove trace amounts of the solvent.

COMPARATIVE EXAMPLE 3

A polyester elastomeric tube is formed by gelation, according to techniques readily understood and commonly practiced by those skilled in the art. This included drawing a 15% solution of a copolymer of poly(tetramethylene ether glycol) and poly(butylene terephthalate), in DMAC into an annulus with a 4 mm center rod and an outer tube with an inner diameter of 7 mm. The mold containing the solution was then placed in a dry ice/acetone bath at -60°C for one minute, and then put in a room temperature water bath for five minutes. The outer shell was then removed and the rod with the gelled polyester elastomeric tube placed in a

room temperature water bath. After an hour the inner rod was removed and the resultant tube washed over several days to remove the residual DMAC.

EXAMPLE 3

A bicomponent yarn is crimped in hot air or water in the absence of tension. This yarn is filament wound at low tension around a 4 mm rod. The rod with the crimped fiber is placed in a mold. A composite tube is formed by drawing a 15% solution of a copolymer of poly(tetramethylene ether glycol) and poly(butylene terephthalate) in DMAC into the mold annulus. The hot tube was placed in a -60°C dry ice/acetone bath for two minutes, and put in a room temperature water bath for five minutes. The outer shell was then removed and the rod with the wound crimped fiber composite gelled polyester elastomeric tube placed in a room temperature water bath. After an hour the inner rod was removed and the resultant tube washed over several days to remove the residual DMAC.

EXAMPLE 4

A polyester tube is formed by warp knitting on a double needle bar knitting machine as is understood by those skilled in the art. A crimped polyester yarn is filament wound around a 4 mm rod and the knit tube placed over the filament wound crimped fibers. A composite tube is formed as in Example 3.

TABLE I

Example #	Kink Radius (in)	Compliance (%/psi)	Burst Strength (psi)	Failure mode
Comparative Example 1	0.5	4	15	catastrophic (> 4 mm)
Example 1	0.4	3	45	localized (< 0.5 mm)
Comparative Example 2	0.5	0.7	36	catastrophic
Example 2	0.4	1.5	>60	localized
Comparative Example 3	0.4	3	16	catastrophic
Example 3	0.25	1.3	22	moderate (~1 mm)
Example 4	0.4	0	24	localized

These examples collectively indicate that the association of crimped fibers together with a polymeric layer to form tubing in general desirably enhances selected physical properties as compared to tubing formed without crimped fibers. Thus, by relating the PEUU tubing of Comparative Example 1 to the same tubing with polyester fiber braids as in Example 1, it is seen that the latter tubing advantageously exhibits a lower kink radius and compliance, a superior burst strength, and less damage to the tube upon failure thereof.

It can be readily appreciated that several modifications to the presently disclosed invention are possible without departing from the spirit and scope herein.

CLAIMS

1. A shaped article comprising an inner layer of cytocompatible material and having an interior surface and an exterior surface, the interior surface defining an aperture therethrough, and one or more crimped fibers disposed about the exterior surface of said inner layer and within an elastomeric matrix.

2. The shaped article of Claim 1 wherein the fibers are linearly disposed about a longitudinal axis of the inner layer.

3. The shaped article of Claim 2 wherein the fibers are disposed in a helical pattern.

4. The shaped article of Claim 2 wherein the fibers are disposed in a radial pattern.

5. The shaped article of Claim 1 wherein the fibers are nonlinearly disposed about a longitudinal axis of the inner layer.

6. The shaped article of Claim 1 wherein the fibers are disposed in a braided pattern about a longitudinal axis of the inner layer.

7. The shaped article of Claim 1 wherein the inner layer is a polyether ester.

8. The shaped article of Claim 7 wherein the polyether ester is a copolymer of repeating units of poly(tetramethylene ether glycol) and repeating units of poly(butylene terephthalate).

9. The shaped article of Claim 1 wherein the inner layer is polyether urethane urea.

10. The shaped article of Claim 9 wherein the polyether urethane urea is a copolymer of repeating units of poly(tetramethylene ether glycol) and repeating units of the reaction product of ethylene diamine with methylene bis(4,4'-diphenylisocyanate).

11. The shaped article of Claim 1 wherein the fiber is polyester.

12. The shaped article of Claim 1 wherein the elastomeric matrix comprises a copolymer of repeating units of a soft segment and repeating units of a crystallizable hard segment.

13. The shaped article of Claim 12 wherein the soft segment is poly(tetramethylene ether glycol) and the crystallizable hard segment is poly(butylene terephthalate).

14. The shaped article of Claim 12 wherein the soft segment is poly(tetramethylene ether glycol) and the crystallizable hard segment is the reaction product of ethylene diamine with methylene bis(4,4'-diphenylisocyanate).

15. A shaped article comprising one or more biocompatible crimped fibers disposed about a longitudinal axis and having an interior surface and an exterior surface, the interior surface defining an aperture therethrough, said fibers being further disposed within a biocompatible elastomeric matrix.

16. The shaped article of Claim 15 wherein the fibers are linearly disposed about the longitudinal axis.

17. The shaped article of Claim 16 wherein the fibers are disposed in a helical pattern.

18. The shaped article of Claim 16 wherein the fibers are disposed in a radial pattern.

19. The shaped article of Claim 15 wherein the fibers are nonlinearly disposed about the longitudinal axis.

20. The shaped article of Claim 16 wherein the fibers are disposed in a braided pattern about the longitudinal axis.

21. The shaped article of Claim 15 additionally comprising one or more fibers axially oriented along the longitudinal axis.

22. The shaped article of Claim 15 wherein the inner layer or the elastomeric matrix or both is porous.

23. A shaped article comprising an inner layer of cytocompatible material and having an interior surface and an exterior surface, the interior surface defining an aperture therethrough and having cells attached thereto, and one or more crimped fibers disposed about the exterior surface of said inner layer and within an elastomeric matrix.

24. The shaped article of Claim 23 wherein the cells are selected from the group consisting of

fibroblasts, adipose cells, endothelial cells, epithelial cells, organ parenchymal cells, muscle cells, nerve cells, cartilage cells, bone cells, and mixtures thereof.

25. The shaped article of Claim 23 wherein the cells are endothelial cells.

26. An article shaped as a vascular graft and connecting a vessel to another portion thereof or to another vessel, said article comprising an inner layer of cytocompatible material and having an interior surface and an exterior surface, the interior surface defining an aperture therethrough and having cells attached thereto, and one or more crimped fibers disposed about the exterior surface of said inner layer and within an elastomeric matrix.

27. The vascular graft of Claim 26 wherein said fibers are linearly disposed in a radial pattern about a longitudinal axis of said inner layer.

28. The vascular graft of Claim 26 wherein the inner layer is a polyether ester.

29. The vascular graft of Claim 28 wherein the polyether ester is a copolymer of repeating units of poly(tetramethylene ether glycol) and repeating units of poly(butylene terephthalate).

30. The vascular graft of Claim 26 wherein the inner layer is polyether urethane urea.

31. The vascular graft of Claim 30 wherein the polyether urethane urea is a copolymer of repeating

units of poly(tetramethylene ether glycol) and repeating units of the reaction product of ethylene diamine with methylene bis(4,4'-diphenylisocyanate).

32. The vascular graft of Claim 26 wherein said fibers are polyester.

33. The vascular graft of Claim 26 wherein the elastomeric matrix comprises a copolymer of repeating units of a soft segment and repeating units of a crystallizable hard segment.

34. The vascular graft of Claim 26 wherein the soft segment is poly(tetramethylene ether glycol) and the crystallizable hard segment is poly(butylene terephthalate).

35. The vascular graft of Claim 26 wherein the soft segment is poly(tetramethylene ether glycol) and the crystallizable hard segment is the reaction product of ethylene diamine with methylene bis(4,4'-diphenylisocyanate).

36. The vascular graft of Claim 26 wherein the cells are endothelial cells.

37. The vascular graft of Claim 27 wherein the fibers are disposed in a braided pattern about the longitudinal axis of the inner layer.

38. The vascular graft of Claim 26 useful in blood vessel bypass procedures wherein said graft connects an artery to another portion thereof or to another artery.

39. The vascular graft of Claim 26 useful to enhance peripheral circulation and wherein said graft connects a blood vessel to another portion thereof or to another blood vessel.

40. An article shaped as a vascular graft and connecting a vessel to another portion thereof or to another vessel, said article further having compliance of greater than or equal to 1% per psi and a burst pressure of greater than or equal to 15 psi, said article comprising an inner layer of cytocompatible material and having an interior surface and an exterior surface, the interior surface defining an aperture therethrough and having cells attached thereto, and one or more crimped fibers disposed about the exterior surface of said inner layer and within an elastomeric matrix.

41. A process for the preparation of a shaped article comprising an inner layer of cytocompatible material and having an aperture therethrough and one or more crimped fibers disposed thereon within an elastomeric matrix, said process comprising:

forming an inner layer of cytocompatible material and having an interior surface and an exterior surface, the interior surface defining an aperture therethrough;

disposing one or more fibers about a fixture configured as the exterior surface of said inner layer to form a reinforcing layer thereon;

transferring said reinforcing layer from the fixture to the exterior surface of said inner layer;

heating said reinforcing layer sufficient to crimp the fibers of said reinforcing layer; and

applying an elastomeric matrix to said reinforcing layer.

42. The process of Claim 41 wherein said inner layer is formed by wet spinning or melt blending.

43. The process of Claim 41 wherein the fixture comprises a plurality of pieces, said pieces being sequentially removed as the reinforcing layer is transferred to the exterior surface of said inner layer.

44. The process of Claim 41 wherein the fixture comprises a plurality of rods collectively configured as the exterior surface of said inner layer, said rods being individually removed as the reinforcing layer is transferred to the exterior surface of said inner layer.

45. The process of Claim 41 wherein the fixture comprises eight rods arranged in a circular pattern and equally spaced from each other, said rods being removed in a sequence such that minimal dishevelment of the reinforcing layer occurs as it is transferred to the inner layer.

46. The process of Claim 41 wherein the reinforcing layer is heated by conduction, convection, or irradiation.

47. The process of Claim 46 wherein the reinforcing layer is heated by air or water.

48. The process of Claim 43 wherein the pieces are rotatably removed.

49. The process of Claim 44 wherein the rods are rotatably removed.

50. The process of Claim 41 wherein the fibers are disposed in a braided pattern about a longitudinal axis of the fixture.

51. The process of Claim 41 wherein the fibers are disposed in a radial pattern about a longitudinal axis of the fixture.

52. A process for the preparation of shaped articles comprising an inner layer of cytocompatible material and having an aperture therethrough and one or more crimped fibers disposed thereon within an elastomeric matrix, said process comprising:

forming an inner layer of cytocompatible material and having an interior surface and an exterior surface, the interior surface defining an aperture therethrough;

disposing one or more crimped fibers about a fixture configured as the exterior surface of said inner layer to form a reinforcing layer thereon;

attaching a tapered structure to one end of the inner layer;

transferring said reinforcing layer from the fixture over the tapered structure and onto the exterior surface of said inner layer; and

applying an elastomeric matrix to said reinforcing layer.

INTERNATIONAL SEARCH REPORT

International Application No PCT/US 91/03904

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl.5 A 61 F 2/06

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl.5	A 61 F

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category °	Citation of Document,[11] with indication, where appropriate, of the relevant passages[12]	Relevant to Claim No.[13]
Y	DE,A,2913510 (INTERMEDICAT) 18 October 1979, see claims 1,3; page 7, lines 23-25	1,5,7, 11,15, 19,22, 23,26, 28,32, 38,39
Y	Textile Progress, vol. 15, no. 3, 1986, (Manchester, GB), B. Pourdeyhimi: "Vascular grafts: textile structures and their performance", pages 1-30, see pages 9-10: "3.3 Crimping"	1,5,7, 11,15, 19,22, 23,26, 28,32, 38,39

-/-

° Special categories of cited documents :[10]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
03-10-1991	24. 10 91
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	M. PEIS. M. Peis

Form PCT/ISA/210 (second sheet) (January 1985)

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)

Category °	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
A	EP,A,0217115 (KANEGAFUCHI KAGAKU) 8 April 1987, see abstract; column 4, line 53 - column 5, line 5; column 6, lines 1-12; column 5, lines 31-44; column 7, lines 25-41; column 8, lines 10-13	5,6,9, 12,15, 19,20, 22,30, 33,37, 38,39
A	Composites Science and Technology, vol. 36, 1989, Elsevier Science Publishers, Ltd, (GB), M.M. Pradas et al.: "An extensible modulus-developing polymer composite", pages 227-241, see page 231, "Experimental"; figure 1 (cited in the application)	1,2,15, 16

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO. US 9103904 SA 49096

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report. The members are as contained in the European Patent Office EDP file on 10/10/91
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

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		JP-A- 62047363	02-03-87
		JP-A- 62064361	23-03-87
		EP-A- 0216149	01-04-87
		US-A- 4725273	16-02-88